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COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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J. Kroneis / T. Gastauer / S. Liu / B. Sauer

Flexible modeling and vibration analysis of a parallel robot with numerical and analytical methods for the purpose of active vibration damping

Abstract

In this paper three different methods for vibration analysis of a planar parallel robot are presented: The two numerical approaches (FEM and MBS) work with models of different discretization levels. In case of analytical modeling the manageability of the resulting equations for closed loop control concepts are besides a sufficient characterization of oscillation behavior a key factor for derivation of active vibration damping strategies for parallel robots. In this paper only the vibration analysis is performed applying the different methods and interpreting the results.

Parallel robots and demonstrator SpiderMill

The mechanical design of parallel robots, with its drives units mounted on the fixed base causes a better dynamical behavior than achievable for classical serial robots. Despite the generally higher structural rigidity of parallel robots (due to sustaining effects of the connected braces) in the workspace these structures still tend to vibrations, especially in case of lightweight constructions for fast pick and place applications. The oscillations cause unwanted errors in the trajectory of the tool center point (TCP) and therefore problems in handling of parts or their machining. As a result, analysis of oscillation behavior and development of appropriate strategies for vibration prevention or damping are research focus. In order to find a strategy also for upgrading of existing mechanical structures no structural optimization of the robot should be performed or any kind of adaptronic components used, but rather a concept for active vibration damping developed. Therefore an extensive vibration analysis and adequate modeling of the oscillation modes have to be accomplished.

Figure 1: The SpiderMill

The planar two DOF parallel robot considered in this paper, called SpiderMill (see Figure 1), comprises a double redundant closed-chain structure, constructed with only revolute joints and standard aluminum profiles. The robot is intended to be used for rapid prototyping. Measurements on the demonstrator exhibit its vibration tendency performing fast movements.

Modeling of the flexible parallel robot

The vibration analysis, which means the identification of eigenfrequencies (and natural modes), is accomplished for the parallel robot using three different methods: Two of them (FEM and partial flexible MBS models) are numerical solutions and one is a new analytical approach. The derived analytical model will also establish the basis for development of active vibration damping strategies for parallel robots.

FEM analysis with ANSYS: Using ANSYS static deformation behavior is analyzed by finite element method for different configurations of the robot. For the modeling of the parts Solid-Modeling method – generating stereoscopic solids – of ANSYS is used exclusively. The created single parts are combined to form a complete model, called basic model, in a second step. Changing the geometric relationships between elements different configurations of the robot are established. Beside different discretization levels for the braces also models with and without bearing stiffnesses are created. Effects of mass inertias and damping are neglected. In contrast to the other presented approaches all parts of the robot are modeled flexible in the used ANSYS model.

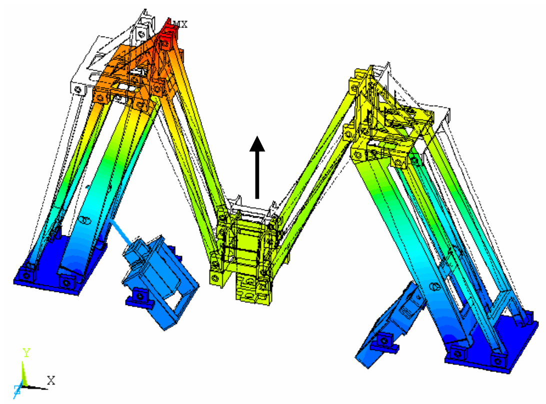

Figure 2: One natural mode

By means of modal analysis the configuration dependent eigenfrequencies and natural modes of the structure are analyzed. The modal analysis implemented in ANSYS is a linear analysis allowing the application of different calculation methods, depending on the application – in our case Block Lanzcos method is used. The first 15 eigenfrequencies (corresponding to a frequency range from 0 to 100 Hz) and natural modes are analyzed. Thereby a calculated linear bearing stiffness is underlying (75 000 M/mm radial, 60 000 N/mm axial). The consideration of more than the first six eigenfrequencies is not necessary due to the fact that these frequencies will cause a dumping of the moving platform which is only possible in a negligible range due to the mechanical structure. For higher natural modes and therefore higher eigenfrequencies it can be recognized that the structural oscillations of the braces and their resulting modes exhibit the main part of TCP displacement. Furthermore, it can be concluded that the lower natural modes describe the movements of the whole structure in all directions (x-y-z), whereas the higher modes present only movements of the structure elements (braces) in working space (x-y-plane).

Flexible MBS in MSC.ADAMS: For complex mechanical structures constructed with many components a classical analytical modeling approach considering all interactions between the single parts is not possible. Also the usually high order of accurate FEM models makes the simulation and analysis of this class of systems, e.g. parallel robots, difficult. Therefore the modeling as a partial flexible multibody-systems (MBS) simulation model gives the opportunity to analyze the statical and dynamical behavior of a robot and also allows the visualization of movements and oscillations.

In the strategy carried out here, a combination between a classical multi-body-system simulation and a FEM approach is established. The rigid bodies of a basic model are partly substituted by flexible elements in different discretization steps. Due to the combination of the strategies most of the inherent disadvantage of both methods can be avoided. Classical MBS approaches can not study flexibilities of components and can perform only a vibration analysis in the lower and middle frequency range. Using FEM only, movements of bodies are reduced to small ranges. Also due to the usually many DOF the FEM approach is limited to linear models (nonlinear couplings of single system components are not regarded). Furthermore system dynamics is not exactly known (boundary conditions and loads are derived mostly from rigid body analysis). Therefore an adequate modeling – especially in the here occurring case of big nonlinear movements of components with a significant influence of their elasticity – requires a combination of both strategies.

For development of the rigid basic model, data from a CAD tool have been imported in MSC.ADAMS. The basic model is improved in several steps regarding (non-)linear elastic bearings (joints), elastic braces and elastic spindles. The calculated nonlinear bearing characteristics are defined as splines. For allowing a direct comparison especially to the analytical approach presented later bearing stiffnesses of the used MSC.ADAMS reference model have been raised. Braces are modeled as deformable bodies with linear-elastic characteristics. To integrate the flexible parts via finite

elements in the MBS model ADAMS/Flex is applied. With the subprogram AutoFlex the rigid braces of the basic model can be described as flexible bodies using Solid Existing Geometry Method or Extrusion Method. Furthermore, it is also possible to import ANSYS data. In our case only the long braces (not the cross members between them) are modeled flexible applying the first method. For the "flexible" modeling of the spindles a length-dependent General Force connecting rigid bodies has been used.
Applying modal approach an elastic deformation is superposed to the rigid body movement of the structure. Thereby the adequate choice of modes is of vital importance. For the model of the SpiderMill a combination of static and dynamic displacement functions (Component Mode Synthesis, CMS) is used. The Craig-Bampton method is applied as CMS technique, where the occurring component modes consist of static displacement modes (Constraint Modes) and modes of motions (Fixed-bonudary Normal Modes; solution of the eigenvalue problem). The disadvantage of the modal approach compared to a discrete one is the only approximative modeling of the stiffness behavior of the robot. But for a mass dominated structure, containing low and high oscillation frequencies and performing linear deformations the modal approach is more suitable than the discrete one and therefore used in our case. As a result of an existing numerical damping, which depends on the solver step size, exact dynamic analysis of the stiffness is not possible. Therefore only analysis of static stiffness behavior is performed. Bearing forces are analyzed by means of statical simulation. Due to the fact that the stiffness highly depends on the configuration of the robot, the whole workspace has to be regarded for an entire analysis.
The implemented MSC.ADAMS models of the SpiderMill are used for dynamic studies regarding loadings of parts or their deformation, respectively. For statical vibration analysis MSC.ADAMS/Vibration is applied. It would also be possible to use models, implemented in a parameterizable manner, for optimization of the mechanical design in the construction phase. But this is not the goal of our approach.

Analytical flexible body model: In a third step an analytical flexible body model of the robot taking the concept of effective payloads into account is derived by applying a hybrid modeling approach. The strategy allows a transient analysis of the eigenfrequencies of the robot during movements, e.g. along different trajectories. For derivation and verification, especially of (rigid) kinematics and dynamics the above mentioned MSC.ADAMS models are used.

Based on a hybrid strategy an analytical description for rigid body kinematics and dynamics is derived: Using the MSC.ADAMS models centers of mass and corresponding point masses are determined especially for complex structural elements like the parallel crank mechanisms. Rigid kinematics is defined by use of standard frame transformations and holonomic constraints. Lagrange's equations of the first type are used for derivation of rigid dynamics. In order to model flexible effects the closed-chain structure is regarded as to serial robots each with two flexible links connected by the moving platform. Moreover, contrary to other flexible body models of parallel robots – where the flexible links have the (rough) form of bars or beams – each beam of the analogous model is regarded separately, taking a configuration dependent effective mass at its tip into account. The masses are calculated using static torque balances of the robot by cutting free the links and solving the Newton-Euler equations for static forces based on equilibrium conditions (see Figure 3).

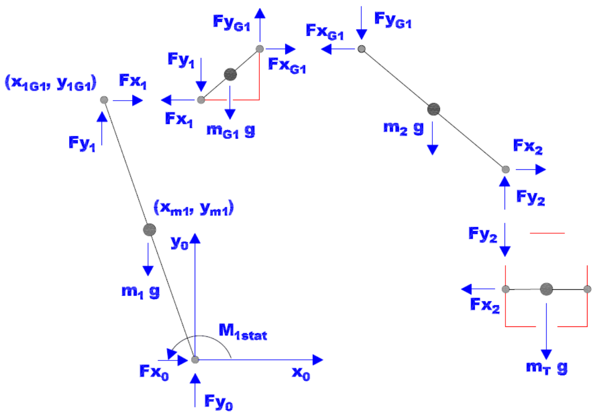

Figure 3: Static forces for the left side

Using Euler-Bernoulli beams and assumed modes method, flexible kinematics and dynamics are derived. The eigenfrequencies of the separate beams as well as the oscillations at the TCP can be calculated for different trajectories, performing a transient analysis. Due to the fact that bearings are regarded as ideal stiff in this first analytical modeling approach their counterparts in the MSC.ADAMS reference model have been adapted for comparison purpose.

Analysis and damping of the critical eigenfrequencies

The critical eigenfrequencies of the parallel robot, especially at the TCP, can be analyzed with all three strategies: To illustrate vibration behavior of TCP eight positions on a reference circle in the motion plane of the robot (z-coordinate is zero, see Figure 4) have been defined and analyzed. The results for the first eigenfrequencies are exemplarily compared for position PK 1 in Table 1. Higher frequencies are not regarded due to the fact that only the low frequencies are critical for accuracy of path and positioning. In general (very) high frequencies can not be damped by active vibration damping concepts, because of their very small time constants.

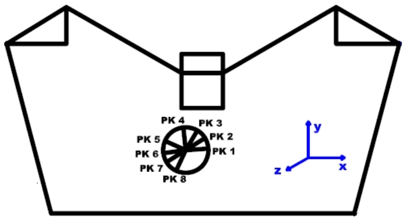

Figure 4: Sketch with reference circle

	x-direction	y-direction
ANSYS	16,48 Hz	20,78 Hz
MSC.ADAMS	42,50 Hz	42,50 Hz
Analytical model	44,74 Hz	44,74 Hz

Table 1: Eigenfrequencies for postion PK 1

Differences between the analytical description and especially the MSC.ADAMS reference model are primarily caused by unmodeled bearing behavior and disregarded effects of the elastic spindles, constraining the free oscillations of the actuated axes of the robot, in the analytical model. Furthermore the analytical model is entire planar. The differences between the frequencies in the ANSYS and MSC.ADAMS models mainly occur due to the full flexible modeling of all bodies and a different description of the bearing stiffnesses in ANSYS. One of the main advantages of the analytical model is also its very short simulation time.

Conclusion and Future Work

In this paper oscillation behavior of a parallel robot has been analyzed applying three different approaches. Thereby occurring (minor) differences of absolute values for the 1st eigenfrequencies have been discussed. To further verify the analytical description, measurements on the demonstrator especially regarding the bearing behavior are necessary. Assured knowledge about occurring frequencies than can be used in open loop control concepts e.g. input shaping of trajectories to damp or even suppress critical frequencies. Moreover, derived and further improved analytical descriptions of flexible kinematics and dynamics form the basis for closed loop control strategies of active vibration damping. Due to the fact that both damping concepts work with the available actuation no constructive changes of the robot are necessary and existing mechanical structures can be upgraded in case of a sufficient dynamic behavior of their drive system.

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